Radiation Tolerant Nanowire Array Solar Cells

Pilar Espinet-Gonzalez[†], Enrique Barrigón[‡], Gaute Otnes[‡,#], Giuliano Vescovi[§], Colin Mann[||], Ryan M. France[⊥], Alex J. Welch[†], Matthew S. Hunt[▽], Don Walker[||], Michael D. Kelzenberg[†], Ingvar Åberg[§], Magnus Borgström[‡], Lars Samuelson[‡,§] and Harry A. Atwater[†,,†]*

[†] Department of Applied Physics and Materials Science, California Institute of Technology, Pasadena, CA 91125, United States

[‡] Division of Solid State Physics, Lund University, Lund, SE-221 00, Sweden

[§] Sol Voltaics AB, Lund, SE-223 63, Sweden

[||] The Aerospace Corporation, El Segundo, CA 90245-4609, United States

[⊥] National Renewable Energy Laboratory, Golden, CO 80401, United States

[∇] The Kavli Nanoscience Institute, California Institute of Technology, Pasadena, CA

91125, United States

[#] Institute for Energy Technology, Kjeller, NO-2007, Norway

[*] e-mail: haa@caltech.edu

Table S.1 Summary of the characteristics of the devices included in each irradiation test.

Particle & Energy	Fluence #particles/cm^2	Solar cell	V_{oc0} mV	J_{sc0} mA/cm^2	V_{oc} mV	J_{sc} mA/cm^2	Area mm^2
p^+ 100 keV	$1\cdot10^{11}$	NW GaAs	933±4	17.5±0.9	839±1	16.6±0.9	1.049
		Planar InGaP	1356±5	8.07±0.1	1160±9	6.50±0.04	10
	$5\cdot10^{11}$	NW GaAs	884±3	16.9±0.2	712±3	14.8±0.5	1.049
		Planar InGaP	1356±5	8.07±0.1	1060±3	5.69±0.02	10
	$1\cdot10^{12}$	NW GaAs	924±9	13.4±0.8	742±1	9.7±0.7	1.049
		NW InP	613±7	16.7±0.1	507±9	15.9±0.3	0.86
		Planar InGaP	1356±5	8.07±0.1	1030±1	4.87±0.04	10
p^+ 350 keV	$1\cdot10^{10}$	NW GaAs	949±11	16.9±0.3	947±8	18.0±0.05	1.049
		NW InP	458±7	15.8±0.4	456±7	16.0±0.5	0.86
		planar GaAs	858±37	18.3±0.08	780±7	18.0±0.2	8.41
	$1\cdot10^{11}$	NW GaAs	912±9	15.9±1.2	887±7	16.1±1.2	1.049
		planar GaAs	950±14	18.4±0.15	644±1	15.3±0.3	8.41
	$1\cdot10^{12}$	NW GaAs	902±6	17.6±0.2	748±2	16.6±0.3	1.049
		NW InP	454±7	15.6±0.6	367±7	14.6±0.5	0.86
		planar GaAs	1014±1	16.1±0.12	454±3	1.8±0.01	8.41
e^- 1 MeV	$5\cdot10^{14}$	NW GaAs	895±5	16.8±0.4	870±4	16.6±0.3	1.049
	$5\cdot10^{15}$	NW GaAs	895±7	16.7±0.04	872±4	16.6±0.04	1.049

	$5 \cdot 10^{15}$	NW GaAs	930±18	17.5±0.5	838±3	16.3±0.9	1.049
		NW InP	635±15	13.4±0.4	635±15	13.2±0.3	0.86

None of the solar cells tested have antireflecting coating.

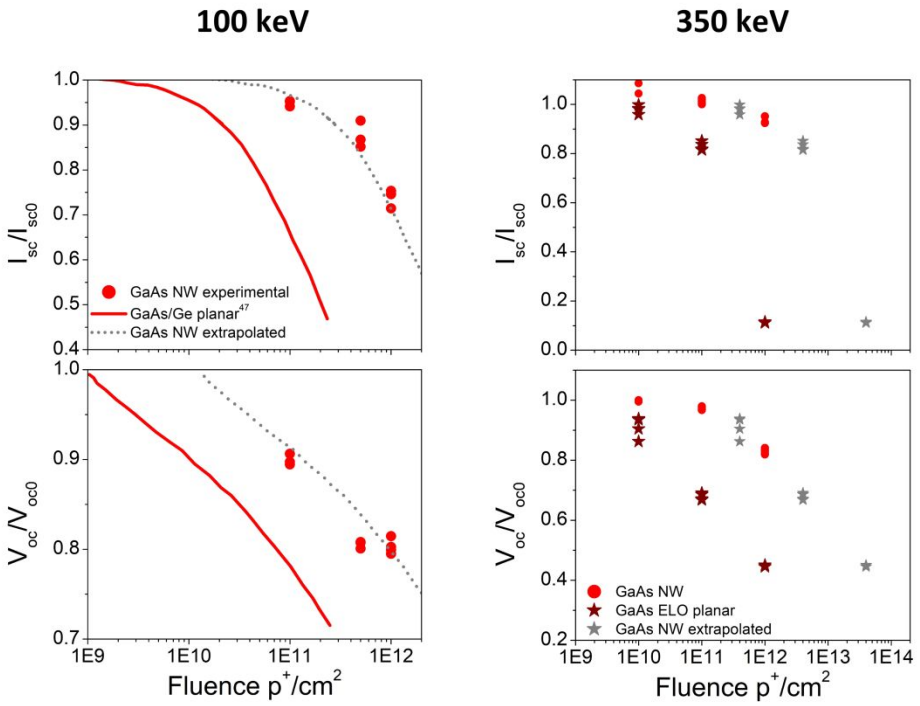

Figure S.1. Comparison of the degradation rate between planar and NW GaAs solar cells under proton irradiation. A correction factor has been used in the planar degradation curves to compare the degradation slope of planar *versus* NW solar cells.

We have applied a correction factor (c) to the planar degradation curves to extrapolate the degradation rate expected in NW solar cells (c (E = 100 keV) = 13 and

c (E = 350 keV) = 40). The extrapolated NW degradation curves (x = $Fluence_{planar}$*c; y = $degradation\ ratio_{planar}$) represented in figure S.1 show a very close match with the degradation data obtained experimentally for the NW solar cells at both energies (100 keV and 350 keV).

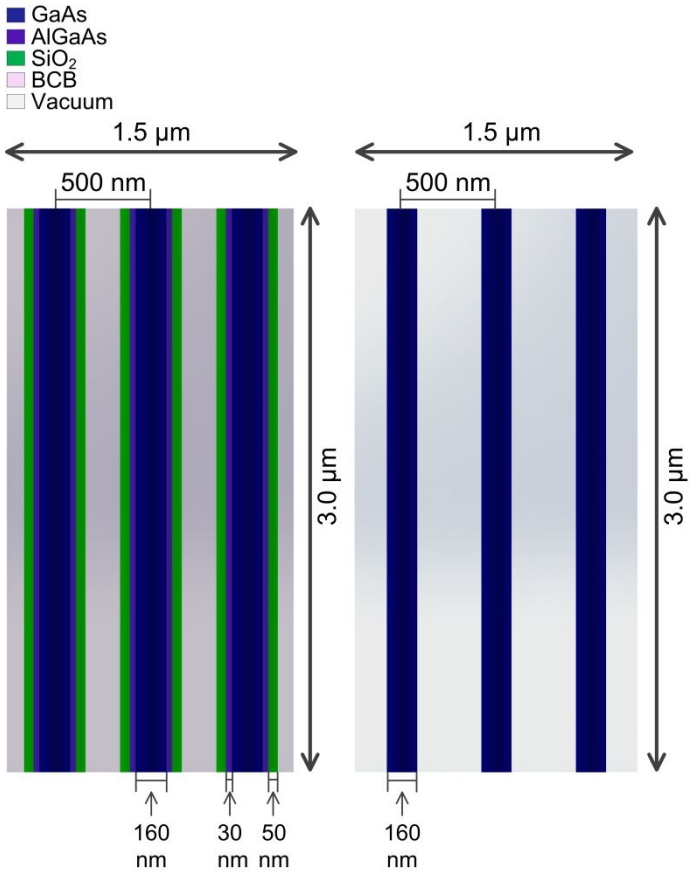

Figure S.2. Cross-section sketch of the NW structures simulated with the Monte Carlo code: core-shell (left) and vacuum (right).

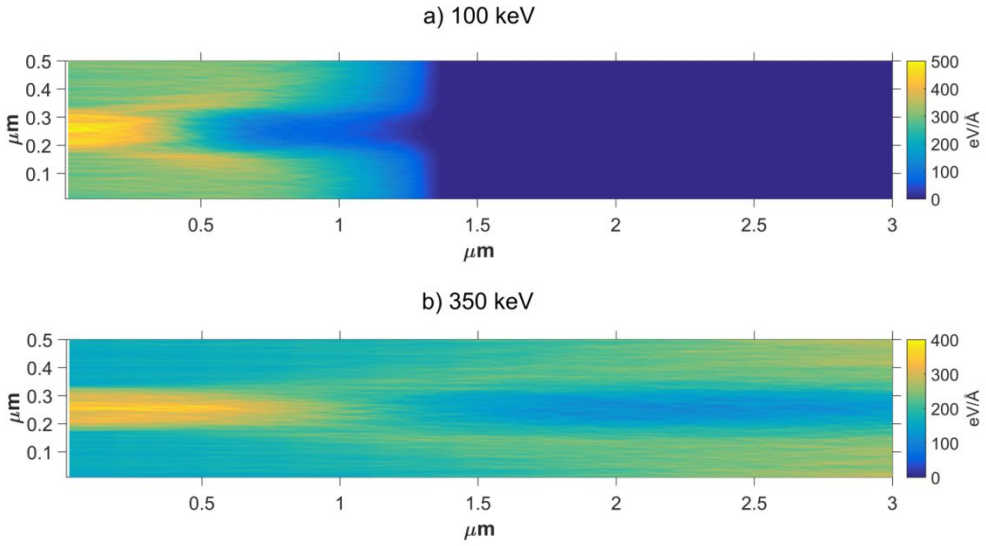

Figure S.3. Electronic energy loss profiles under the irradiation with normal incident protons. False color maps representing the integrated electronic energy loss over the NW diameter (160 nm) under the irradiation with 100 keV protons (a) and 350 keV protons (b).

In order to simplify the interpretation of the simulations basic NW arrays have been modeled. The NW array consists of a GaAs NW with a radius of 80 nm and a pitch of 500 nm infilled with BCB. Periodic boundary conditions have been considered laterally. No core-shell of $Al_{0.9}Ga_{0.1}As$ or SiO_2 insulating layer has been included in the

simulations. An increment on the electronic power loss in the BCB around the NW due to scattered ions from the GaAs NW is particularly noticeable at a depth >250 nm and >750 nm in the irradiation with 100 keV and 350 keV respectively.

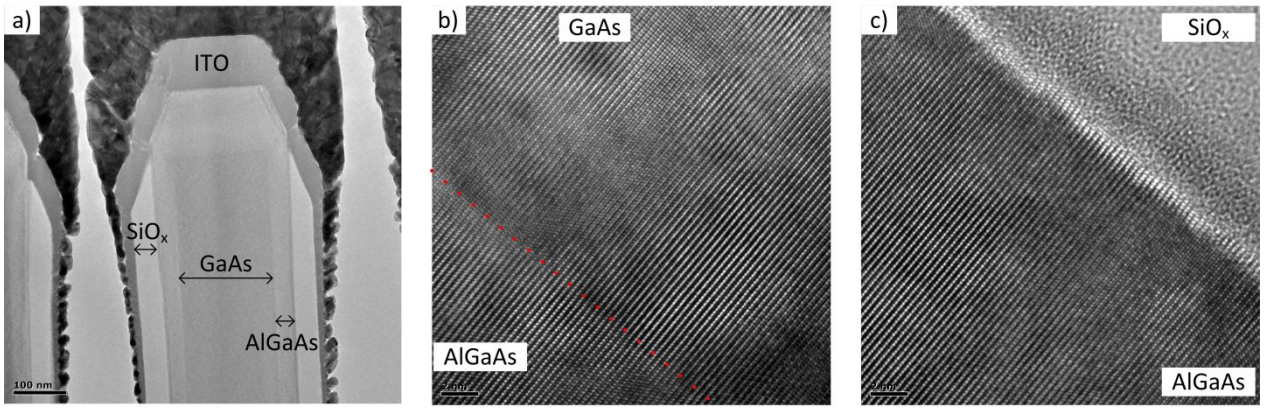

Figure S.4. Transmission electron microscopy images of a NW solar cell irradiated with 100 keV p^+ at a fluence of 10^{12} p^+/cm^2.